THE 60 MeV GRENOBLE ISOCHRONOUS CYCLOTRON

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ABSTRACT. This article describes the 60 MeV variable energy isochronous Cyclotron designed and constructed by C S F. for the University of Grenoble A general description of the machine along with method of calculations, operational characteristics and the special features are given

INTRODUCTION

In a cyclotron the charged particles are submitted to a magnetic induction in a direction perpendicular to their velocity, which forces them to follow circular trajectories at the frequency of rotation $\omega = eB/m$. An electric field provides one or several accelerations per turn, which increases their energy and consequently the radius of their trajectory.

But an increase of energy in this way in a cyclotron is limited to 20 to 25 MeV protons due to the increase of mass of the particles with velocity, and the frequency of rotation is no longer constant.

$$\omega = \frac{eB\sqrt{1-\frac{v^2}{c^2}}}{m_0}$$

In an isochronous cyclotron this limitation is overcome by varying the magnetic field from the centre to the edges The radial variation of the magnetic induction compensates for the relativistic variation of the mass :

$$B = \frac{B_0}{\sqrt{1-\omega^2 r^2}}$$

where B_0 is the value of the induction at the center.

The velocity of the rotation is thus maintained constant. It is then possible to obtain a continuous emission of particles, and a beam of much higher average power.

The progressive increase of induction as a function of radius induces a vertical defocussing effect. This is compensated by azimuthal variation of the magnetic field. This azimuthally varying field is created in the median plane by means of alternate regions of strong (hills) and weak (valleys) fields This, on the other hand, distorts the circular trajectory of the particle which takes the form of a curvilinear polygon The effect of focalisation can be further improved by spiraling the sides of the hills in such a way that the angle of entrance into the hill region is increased and that of the angle of departure is decreased

The index of the magnetic field is expressed by the relation .

$$n = -\frac{\rho}{\beta}\frac{d\beta}{dx}$$

ρ being the radius of curvature of the trajectory and x the distance measured normally to the trajectory. In an isochronous cyclotron the magnetic field B as well as x are functions of r and θ and this leads to the use of the term ' average' index in the theory of these machines and defined by .

$$K = \frac{r}{<B>} \cdot \frac{d<B>}{dr}$$

where the quantity in the brackets represents average value on the closed orbit. It can be shown that .

$$K = \frac{\dfrac{\omega^2 r^2}{c^2}}{1-\dfrac{\omega^2 r^2}{c^2}}$$

The relation between K and the energy of the particle is expressed by ·

$$E = E_0(\sqrt{K+1}-1)$$

where $E_0 = m_0c^2$, the rest energy.

From this equation the curves of the Figure 1 have been drawn. The values of K for isochronous field for protons are given below

0.11 for 50 MeV	0.165 for 75 MeV	0.202 for 90 MeV
0.225 for 100 MeV	0.26 for 115 MeV	0.30 for 150 MeV

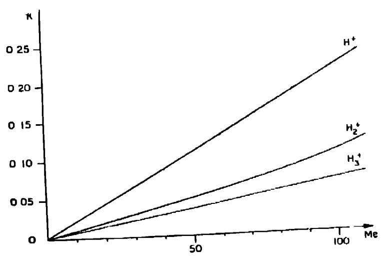

Fig. 1. Variation of the field index with energy for different particles.

The Grenoble machine is a variable energy four sector isochronous cyclotron to give external beams of 60 MeV protons, 30 MeV deuterons, 20MeV tritons and 60MeV α-particles. It has been designed for high performance and is comparable in energy to the cyclotrons of Berkely and Oak-Ridge

ELECTRO-MAGNET

The electro-magnet of this cyclotron has been designed with enough margin preserved for easy adjustment at all the energies

Consideration for deuteron acceleration led to the choice of 1 52 teslas (Fig 2) as the maximum average field at the radius of extraction which was fixed at 0.86m, having possibility of using 0 9m, if necessary, for extraction purposes. The flux needed at the radius of extraction is therefore $1\ 52 \times 0\ 86^2 = 3\ 53$ Webers and the model studies show that a total flux of the order of 6 35 Webers is needed to obtain the required field strength

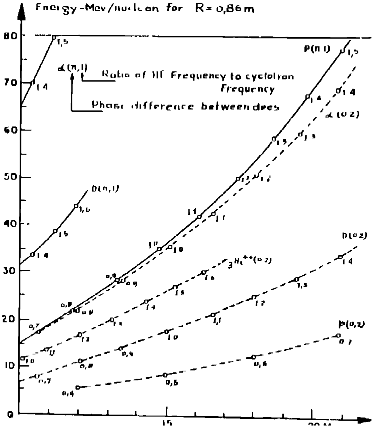

Fig. 2. Operational curves.

A yoke of moulded steel has been chosen. Its maximum permissible induction is 1.7 teslas. Total area of the yoke must therefore be at least $\frac{6.35}{1.7} = 3.74\text{m}^2$.

The frame was moulded with A48M3 steel of the Société des Forges et Acieries du Creusot (France) and the poles were forged in A11V steel. The composition of these steels are given in table I.

TABLE I

Composition of the metal of the electro-magnet

	Impurity %		*Mn*		*S*	*Si*	*Ni*	*Cr*	*Cu*	*Co*
A 48 M 3	limit	0.25	0.75	0.03	0.025	0.35		0.15		0.02
	average	0.25	0.63			0.23				
A 11 V	limit	0.07	0.5	0.03	0.03	0.2	0.2	0.2	0.2	0.00[illegible]
	average	0.055	0.45	0.015	0.01	0.15				

The content of Cobalt was specially checked to avoid any danger of activation. The homogeneity was tested by means of ultrasonics

The total gap comprises of 0.166m between the hills and two spaces of 9mm under the hills for returning the auxiliary coils, thus making a total of 0.184m. The ampere turns necessary for a maximum induction of 2 teslas is

$$NI = \frac{2 \times 0.184}{4 \times 10^{-7}} = 307{,}000\ AT.$$

The iron of the yoke requires 8000 ampere-turns per meter for an induction of 1.7 teslas. So with average length of 6 meters it needs 48,000 ampere-turns

TABLE II

Characteristics of the Electro-magnet

pole diameter		2,02 m
root diameter		2,15 m
root cross section		3.05 m²
yok cross section	minimum	1.87 m²
	maximum	2.0 m²
gap between hills		0.166 m
gap between valleys		0.405 m
Maximum flux		7.3 W
yoke induction	minimum	1.82 T (H 12,000 AT/m)
	maximum	1.95 T (H = 20,000 AT/m)
weight		200 tons
Main coil		
number of turns per coil		180
total number of turns (2 coils)		360
total length of the conductor		2,900 m
weight of the copper		6,800 kg
weight of a coil		4.100 kg
capacity of the power supply		1.100 A
maximum power of the power supply		300 kW
applied voltage		264 V

which is supplied by two coils of five pan-cakes of 36 turns each, making 360 turns in total The conductor is a copper bar of 17.6×17.6 mm with a central hole of 9.7mm dia. for the circulation of the cooling water. Each coil is moulded in araldite under vacuum and pressure inside a non-magnetic stainless steel casing The cover-plate along the gap is made of aluminium to suppress any possible modulation of the fringing field by the high frequency harmonics of the supply current Each pancake is wound with two conductors in parallel to reduce the loss of head into the colling circuit. All coils are therefore connected electrically in series and hydraulically in parallel.

For the normal intensity of 1000 amperes as envisaged the power consumption is 230 kW with cooling water consumption of 7.2m^3/h.

The main characteristics of the electromagnet are given in table II.

Four sectors are mounted on the flat pole-face forming the valley floor. During the operation the field shape can be varied by means of 10 circular coils on each pole There are 4 valley coils, 8 hill coils and 4 harmonic coils on each pole for field corrections and harmonic control.

Power consumption in the auxiliary coils is 140 kW in comparison with 230 kW in the main coil. This is a characteristic of the isochronous cyclotron. In cyclotrons of 100 MeV energy and above, this consumption may exceed the power in the main coils.

The stability of the power supply of the main coils is better than 10^{-4}. The current in the coil is measured by placing a high precision shunt across it. The shunt is cooled by water whose temperature is regulated. The voltage measured across it is compared with a reference voltage of high stability. The difference between these two voltages is chopped to feed an a.c. amplifier. The amplified output is demodulated and it serves to command ballast transistors. The d.c voltage at the beginning is obtained from a six phase rectifier making use of silicon diodes. The diodes and the transistors are also cooled by water. The stability of the power supply of the correction coils is 10^{-3} A device consisting of diodes and transistors has been incorporated in the main coil power supply to absorb the stored power in the electro-magnet in case of power failure.

RF SYSTEM

A recent system consisting of two resonant cavities and two accelerating electrodes (dees) has been found most suitable for this cyclotron. The frequency range to be covered has been determined from the energy requirements and the magnetic field according to the fundamental relation $\omega = \frac{eB}{m}$. Fig. 3 shows the dispositions of different elements of the Grenoble cyclotron. The great advantage of the two-cavity accelerating system is that two large regions of 90° opening, easily accessible from outside, are available for extraction.

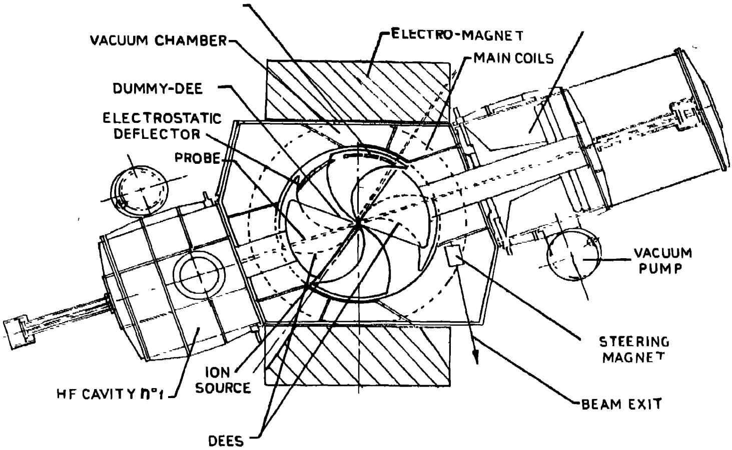

Fig 3. Top-sectional view of the Grenoble cyclotron

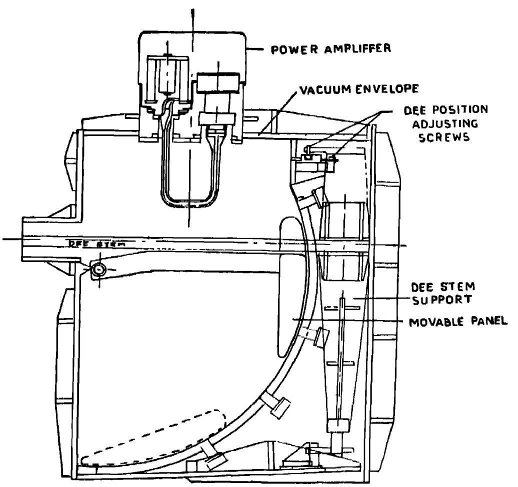

Fig. 4. Side-sectional view of a resonant cavity.

Fig. 2 shows that to satisfy these requirements, the frequency must be adjustable from 10.5 to 21 Mc/s.

Cavity adjustment for change of frequency is done by displacing a contactless capacitive panel inside it (Fig 4) This structure was chosen after an extensive study of a 1 · 5 model The characteristics of one of the cavities are shown in Fig. 5 and 6. The results are particularly satisfactory and they show that this structure avoids the lowering of the Q-factor at higher frequencies.

Point by point electric field measurements with capacitive probes show that the $r-f$ high voltage is constant all along the dee in the desired frequency range. The magnetic field measurements along the dee-stem shows that the high frequency current is constant in the lower range. But a small peak appears at high frequency if the arm of the moving panel is not parallel to the dee-stem At high frequency the currents are equal in the stem and in the arm of the mobile panel.

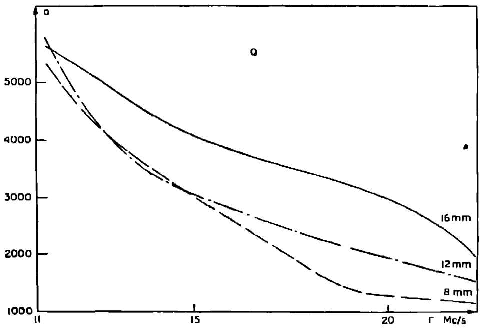

Fig 5. Q-factor of the cavity as a function of frequency.

The $r-f$ drive system consists of a master oscillator and a chain of amplifiers The power tubes are ceramic metal tetrodes (RS 1082 Siemens) capable of delivering nearly 50 kW up to a frequency of 30 Mc/s. Each tube is mounted directly on its cavity to avoid problems of cable connections. Cooling water for the anodes circulate through the coupling loops thus avoiding problems of high frequency isolation of the water circuit

These tubes are fed by a distributed amplifier (Marconi HS 113) whose gain and power are constant from 4 to 24 Mc/s without any adjustment. The amplifier itself receives signals from a frequency synthesizer. Actually, besides the frequency adjustment of the pilot and the cavity, the complete chain has only one adjusting point in the grid circuit of the tetrode. The grid is always fed at low impedance, thus avoiding any neutralization of the final stage A low impedance broad band circuit is under consideration to suppress this adjustment too.

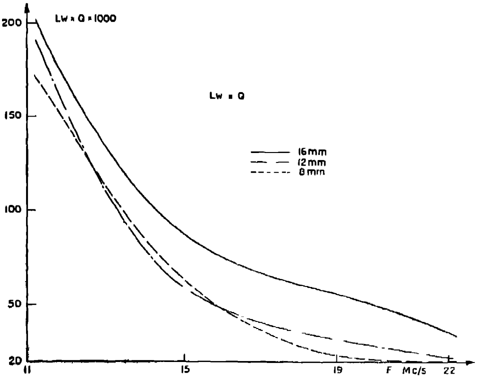

Fig 6 Impedance of the cavity as a function of frequency

MAGNETIC FIELD MEASUREMENTS

For precision measurements of the magnetic field the floating wire (hodoscope) method has been adapted, thus supplying directly the required information regarding the stability of the particles. Along with it the usual method of taking magnetic field readings and deducing the characteristics of the motion of the particles by means of a computer has also been used for comparison Details of these techniques have been described by Aucouturier (1964).

VACUUM

The vacuum is maintained by means of a pumping system whose capacity is 16 000 l/sec This comprises two diffusion pumps placed on the cavities. The pressure maintained is better than 10^{-5} torr

INJECTION

Along with the conventional internal injection, this cyclotron has been designed for an external injection system . a beam of particles may be transmitted axially by a hole on the yoke. A series of electrodes defines the beam injected in the central region to insure the best quality for the accelerated beam. Auxiliary coils taper the magnetic field in the vicinity of the axis for optimum value for best focussing. Axial injection will be used for acceleration of polarized particles, since it is thus possible to avoid pollution by non-polarized ions.

The ion source for the internal injection is of the Livingstone–Jones type where a beam of electrons emitted from a hot tungsten filament ionizes the gas molecules injected into an axial cylindrical chamber. The ion sare extracted by a lateral slit and injected into the cyclotron by the r—f voltage. The consumption of gas is at the rate of about 1 cm^3/min. The arc voltage and current are of the order of 200 V and 5A respectively.

EXTRACTION

The extraction system consists of an electrostatic deflector followed by a magnetic channel A radial disturbance is induced in the region of the outside trajectory to enable the beam to pass into the electrostatic deflector. This deflector displaces the beam from 10 to 15 mm to enter the magnetic channel which is an assembly of steel bars forming a kind of magnetic shield. A coaxial type of extractor as used in Oak-Ridge is also being studied for this purpose.

Centering of trajectories, observed with the help of probes, is adjusted by means of correcting coils An optical system comprised of focussing triplets and of analysing magnet continues the extraction (Fig. 3).

CONCLUSION

Because of the possibility of choosing independently the $r-f$ frequency, the average magnetic field, and the magnetic field pattern, this cyclotron can be used to accelerate particles of different mass · protons, deuterons, tritons, α, heavy nuclei and for each one a continuously variable energy output is obtainable.

Tests on the component parts of the machine have been completed and found satisfactory justifying design calculations and model studies Final installations are being carried out to run the machine next year.

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